CURRENT DEVELOPMENTS IN FUTURE PLANETARY PROBE SENSORS FOR TPS

Ed Martinez[1], Ethiraj Venkatapathy[2], Tomo Oishi[3]

[1] *NASA Ames Research Center, MS 229-4, Moffett Field, CA 94035 (USA), Email: Ed.Martinez@nasa.gov*
[2] *NASA Ames Research Center, MS 229-3, Moffett Field, CA (USA), Email: Ethriaj.Venkatapathy-1@nasa.gov*
[3] *Tomo Oishi, Ion America, MS 229-4, Moffett Field CA 94035 (USA), Email: toishi@mail.arc.nasa.gov*

ABSTRACT

In situ Thermal Protection System (TPS) sensors are required during reentry to provide traceability of TPS sizing tools, design, and material performance. Traceability will lead to higher fidelity design tools, which in turn will lead to risk reduction and decreased heatshield mass on subsequent missions requiring atmospheric aerocapture or entry/reentry [1]. Decreasing heatshield mass will enable certain missions that are not otherwise feasible and directly increase science payload and returns [2].

We consider two flight measurements as essential to advancing the state of TPS traceability for material modeling and aerothermal simulation: heat flux and surface recession (for ablators). The heat flux gage is applicable to both ablators and non-ablators and is therefore the more generalized sensor concept of the two, with wider applicability to mission scenarios.

This paper describes the development, from NASA's Technical Readiness Level (TRL) 3 to 6, of a microsensor capable of surface and in-depth temperature and *heat flux* measurements for heatshield materials appropriate to Titan, Neptune, and Mars reentry. Progress to adapt a previously flown surface recession sensor, Galileo's Analog Resistance Ablation Detector (ARAD) [3], to appropriate advanced aerocapture ablators is also discussed. Demonstrating quantitative sensor operation and functionality under relevant ground test environments would achieve TRL 6, defined as prototype demonstration in a relevant space or ground environment.

1. THERMAL SENSOR OVERVIEW

A primary requirement of TPS sensors is to make in situ measurements of aerothermal environments. This data would provide anchor points to base evaluation and improvement of CFD and TPS response models, thereby reducing future flight uncertainty. A temperature and heat flux gage, currently at TRL 3, would provide a miniaturized low mass (~1 gram, 1 cm diameter) sensor with minimal impact to spacecraft weight and power requirements. The sensors consist of a thermal diffusion barrier (~500 microns thick) of refractory ceramics sandwiched between Platinum films (10 microns thick) as resistance thermometers, or resistance temperature detectors (RTDs) [4]. The sensor production process uses thick film printing, and ceramic tape casting technology [5]. Fourier's Law is used to calculate conducted heat flux from the temperature difference across the thermal barrier [6]. Irradiated heat flux, out from the sensor, is given by the emissivity and temperature of the sensor. Via energy balance, the sum of the two is equal to the incident heat flux. Choice of materials and critical dimensions are used to tailor gage response to specific (forebody vs. aftbody) heating environments. Absolute upper limits of temperature are given by the melting points of the materials: 2045K for Platinum; and 2323K for alumina, although 1500K is a more realistic upper bound [7]. Assuming radiative equilibrium ($q=\varepsilon\cdot\sigma\cdot T^4$) at 1500K, and an emissivity of 1, gives an expected maximum allowable constant heat flux of $q=28.7$ W/cm^2. This range is ideally suited to Titan, Neptune, and Mars aftbody TPS surface locations, as well as some Mars Science Laboratory forebody locations. When peak flux loads exceed 28.7 W/cm^2 by significant amounts, the sensors can be imbedded beneath the forebody TPS surface to measure in situ temperature and conduction through a highly characterized thermal buffer. The temporal response of the gage itself depends on its thickness, thermal properties, attachment method, and backface boundary condition, which is governed by the attachment technique and TPS design. The temporal response of the measured heat flux depends on how the temperature data is analyzed, and can be as fast as the time constant of the gage. Typical gage time constants vary between 0.05 to 0.2 seconds. The superior time response allows for measurement of the time at transition to turbulence, another key modeling parameter. Thorough calibration of the sensor is required due to the variation of thermal properties with temperature. For example, the thermal conductivity of the ceramic barrier can vary by a factor of 5 over the range of sensor operational temperatures.

2. QUANTIFYING HEAT TRANSFER COMPONENTS

An array of the heat flux gages can be used to quantify heat flux components. Through the use of appropriate coatings, catalytic and radiative sensitivity of the heat flux gage can be tailored. By co-locating gages with selective surface coatings, data can be obtained to isolate heat flux components due to radiation, catalycity and convection within a 3 cm diameter location. A simple schematic is illustrated in Fig. 1.

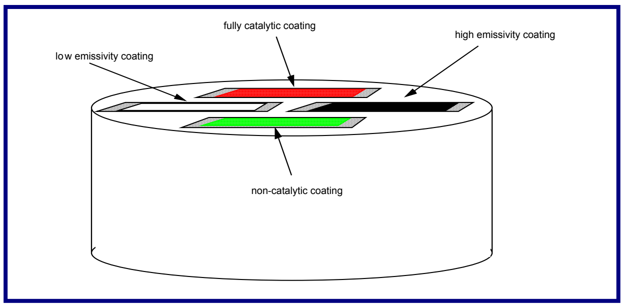

Fig. 1. An integrated TPS plug concept with multiple sensors co-located to measure total heat flux and the components to provide fully catalytic, non-catalytic, high and low emissivity components.

3. CURRENT STATE OF THERMAL MICROSENSOR

The heat flux sensor has been laboratory tested by exposing it to a chopped hot air gun to demonstrate response to a rapidly changing thermal environment. Fig. 2 shows this response, and Fig. 3 shows a typical gage.

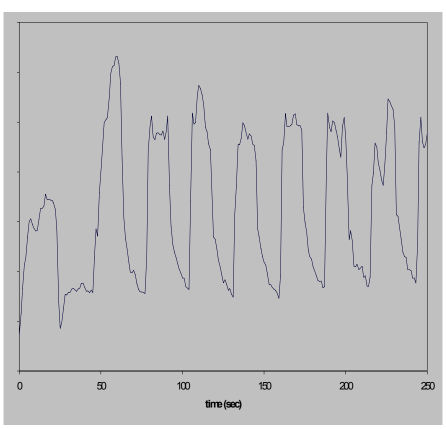

Fig. 2. Flux gage output to chopped hot air.

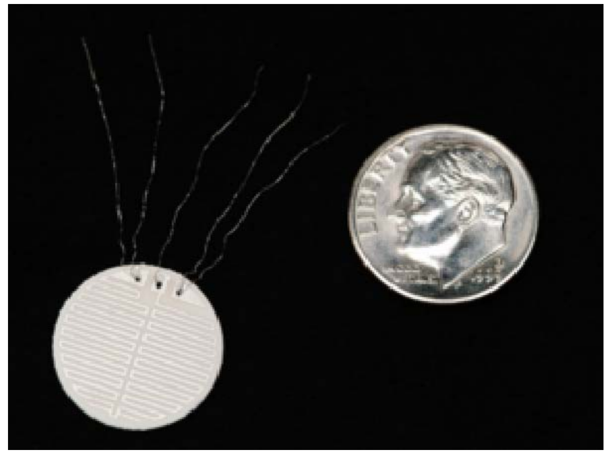

Fig. 3. Photo of flux gage.

Calibration of the device requires material property characterization. Fig. 4 is the simulated gage response to a triangular heat pulse with duration of 60 sec. Fig. 5 is a series of simulated calibration curves relating temperature difference across the alumina, front face temperature, and absorbed heat flux.

Three prototype heat flux sensors were tested for its temporal response [7]. Periodic heating is applied by a chopped laser and gage output is recorded. Typical response is shown in Fig. 6.

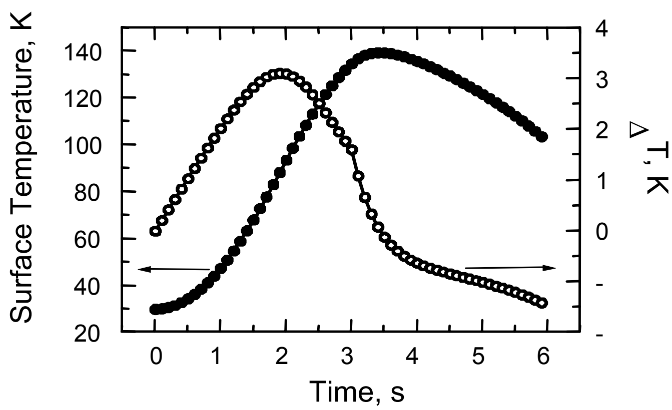

Fig. 4. Simulated surface temperature and ΔT as a function of time during ramped application of heat.

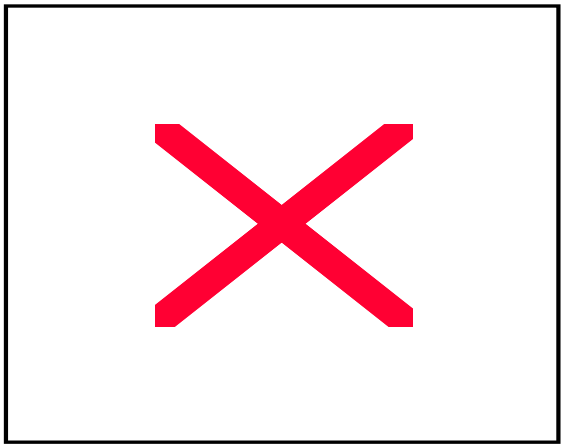

Fig. 5. Simulated calibration curves for several values of applied heat flux.

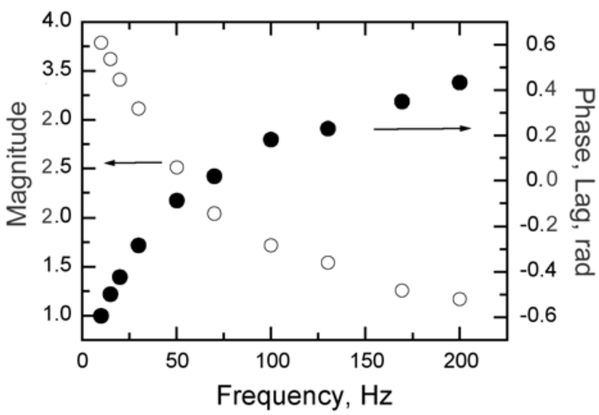

Fig. 6. Heat flux gage response to periodic laser heating.

An experimental approach was implemented to investigate the use of periodic heating to determine sensor thermal properties. A strip of alumina wafer was exposed to an argon-ion laser while mounted in a vacuum chamber. The thermal properties can be obtained from the amplitude and phase lag of the temperature of the strip measured at various distances from the laser. Fig. 7 shows experimental data obtained using a laser at 8 Hz to provide spot heating over an area of 0.1 mm. This is an excellent approach to quantifying material properties because absolute magnitude of the laser power is not important.

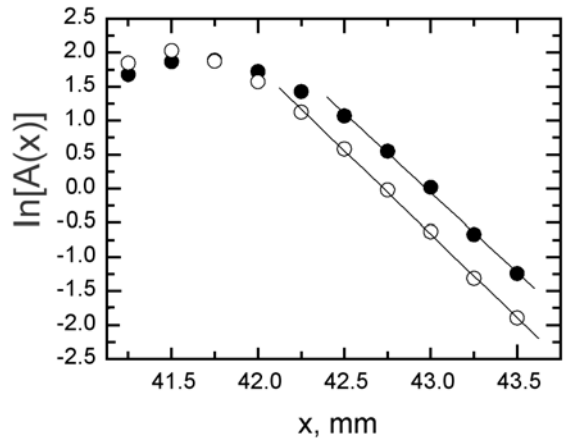

Fig. 7. Log of temperature increase as function of distance from the laser source

The thermal sensor system offers many advantages over traditional thermocouples. First, because of the way in which it can be tailored, components of heat flux can be measured. Second, because the sensor uses a thermal barrier of well characterized material, the measurement is independent of the TPS material. A traditional thermocouple approach must rely on the material response model of TPS to infer incident heat flux, and in no way can provide an independent measure of heat flux components.

4. RECESSION SENSOR

The ARAD sensors were comprised of a narrow (~2 mm diameter) rod of carbon phenolic (forebody material) wrapped with alternating layers of insulating tape (Kapton), Platinum-Tungsten wire, more insulating tape, and Nickel ribbon [8]. The resistance of the Platinum-Tungsten wire was much higher compared to that of the Nickel. ARAD functionality is based on the fact that char produced by the ablating phenolic and Kapton is electrically conductive. An electronic circuit supplied a constant current, as excitation; the Platinum-Tungsten wire, char and phenolic loop complete the circuit. The voltage is measured across Nickel sensing wire and the Platinum-Tungsten wire. As the phenolic ablated and recessed, the Platinum-Tungsten wire shortened and its resistance decreased. Arc jet testing demonstrated a resolution of ±0.09 cm recession, for a maximum 0.1 cm/s recession rate. Flight data analysis indicated stagnation point recession of 4.13 cm with instrumental uncertainty of ±0.25 cm. A single sensor, with an outer diameter of approximately 1 mm and a length of ~50 mm, would weigh less than 10 grams.

A major design feature of ARAD was its use of TPS material as the core support for the Platinum-Tungsten sensing element, assuring that sensor recession matched that of the forebody. Because the Galileo high-density carbon-phenolic forebody material is an unlikely choice for aerocapture aeroshell TPS, we consider the ARAD sensor concept to be at TRL 3. The original design will be adapted to future needs by substituting advanced TPS materials for the original carbon phenolic core. The TRL 6 level will be demonstrated during arc jet calibration of the modified sensors installed as integrated components of appropriate TPS plugs.

5. SUMMARY

The current effort will develop a new robust and reliable sensor *system* for the in-flight measurement of critical aeroshell performance parameters: total heat flux, and heat flux magnitudes due to catalycity, convection, and radiation. The ARAD effort will adapt a flight-demonstrated recession sensor design for advanced Titan and Neptune TPS ablators.

These measurements will provide the critical link for traceability from ground to flight validation data necessary to refine the aerothermodynamic and material response models upon which future vehicle designs are dependent. Improving these models would reduce uncertainties in TPS mass, either increasing scientific yield while reducing mission risks and/or allowing for less expensive launch vehicles. The engineering data these sensors provide would expand the set of entry scenarios for which aerothermal conditions and TPS response can be predicted with confidence; it is essential for efficient exploration of the outer planets and their moons possessing atmospheres.

6. REFERENCES

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